

## Evaluation of Coaxial Single Range Thermal Voltage Converters With Multijunction Thin-Film Thermoelements

Thomas F. Wunsch, Ronald P. Manginell, Otis M. Solomon

Sandia National Laboratories\*  
Albuquerque, NM 87185-0665 USA

Phone: (505) 844-4359, Fax: (505) 844-7699, E-Mail: tfwunsc@sandia.gov, WWW: <http://www.sandia.gov/psl>

Joseph R. Kinard, Thomas E. Lipe

Electricity Division  
National Institute of Standards and Technology\*\*  
Gaithersburg, MD 20899-8111 USA

Phone: (301) 975-4250, Fax: (301) 926-3972, E-Mail: joseph.kinard@nist.gov, WWW: <http://www.eeel.nist.gov>

Kenneth C. Jungling

Department of Electrical and Computer Engineering  
University of New Mexico  
Albuquerque, NM 87131 USA

Phone: (505) 272-7892, Fax: (505) 277-1439, E-Mail: ken@eece.unm.edu, WWW: <http://www.eece.unm.edu>

***Abstract*** - The National Institute of Standards and Technology and Sandia National Laboratories are developing new thin-film multijunction thermal converters (MJTC) for use as standards of ac-dc difference. Elements of the fabrication process allow control of various features of the device affecting the optimal configuration (e.g. thermal time constant, heater resistance, etc...). A negative ac-dc transfer difference, caused by a capacitive coupling of ac signal to the silicon obelisk, is observed in devices with a silicon obelisk at high-frequency. A circuit model illustrates the dependence of this difference on the substrate resistivity. Devices that are assembled in a coaxially mounted single-range thermal voltage converter configuration are discussed.

### I. INTRODUCTION

An initial difficulty in the development of the thin-film multijunction thermal converter [1,2] was the failure of the device to fully integrate low-frequency ac waveforms due to the small thermal time constant of a few milliseconds. This led to investigations by Klonz and Weiman that increased the time constants to a few seconds by incorporating a mass of silicon directly beneath the heater [3]. Unfortunately, the addition of a silicon feature beneath the heater, while increasing the thermal time constant and improving low-

The silicon feature is referred to as an "obelisk" in the literature.

This negative ac-dc transfer difference effect, which is dependent on the frequency of operation and the resistance of the thermoelement, has not been fully understood [4]. Its presence has been attributed to dielectric losses, although the negative ac-dc difference is not observed in devices without the silicon obelisk feature.

The National Institute of Standards and Technology and Sandia National Laboratories are developing new thin-film multijunction thermal converters (MJTC) for use as standards of ac-dc difference. In order to produce a single device capable of operation over the frequency range of 10 Hz to 1 MHz that is suitable for replacement of single junction thermoelements, it is necessary to understand and control the aforementioned effect along with other sources of transfer difference at high-frequency.

The elements of the microfabrication of the device have been recently reported [5,6]. After briefly reviewing these concepts, this paper will discuss the assembly and evaluation of the thermoelement in a coaxially mounted single-range thermal voltage converter configuration. Elements of the fabrication process allow control of various parameters of the device affecting the optimal configuration (e.g. thermal time constant, heater resistance, etc...). A newly developed model shows that control of these parameters as well as the resistivity of the substrate material, the dielectric thickness,

\*Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

\*\*NIST is part of the Technology Administration, U.S. Department of Commerce.

frequency ac-dc transfer difference, has the unintended effect of producing a negative ac-dc difference at high-frequency.

and the temperature of operation influence the magnitude of the negative ac-dc transfer difference at high-frequency.

## II. THIN-FILM CONSTRUCTION

Construction of a thin-film thermal converter requires the microfabrication of each component of a conventional MJTC be fabricated on a device that has the scale of a few millimeters on a side. The components include the heater, the thermopile, and the supporting substrate. Figure 1 shows a conceptual drawing of a thin-film MJTC. Metallic heater and thermocouple materials are sputtered using standard thin-film processing techniques. The silicon substrate acts to thermally isolate the device from changes in ambient temperature, and a thin-film dielectric membrane isolates the heater and thermopile “hot junctions” from the thermopile “cold junctions”. This thermal isolation allows a temperature gradient to be developed across the thermopile. The temperature gradient generates a Seebeck emf in the thermocouple circuit that serves as the output signal of the thermoelement.

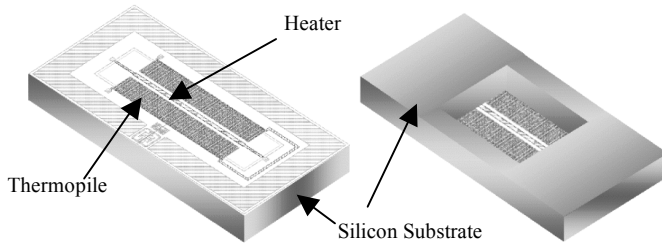


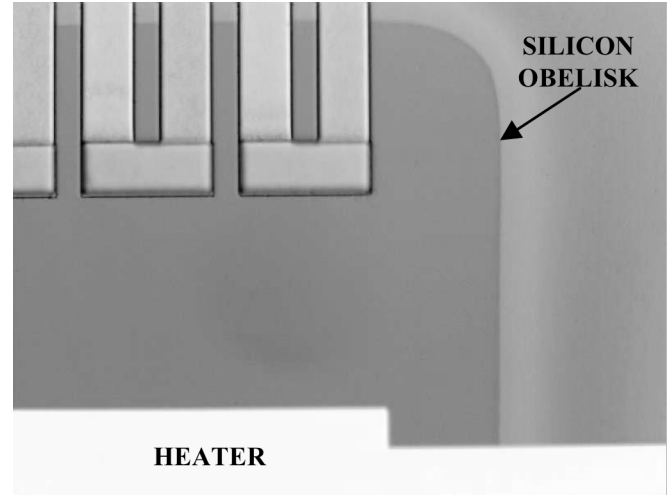
Figure 1. A conceptual drawing of a thin-film MJTC (6 mm x 3 mm x 0.4 mm) with 100 series connected thermocouples and a 400  $\Omega$  heater. On the left is a top perspective view. On the right, is a perspective view of the back-side of the die. The thermopile and heater are visible through the transparent dielectric membrane in the bottom view.

## III. MICROFABRICATION

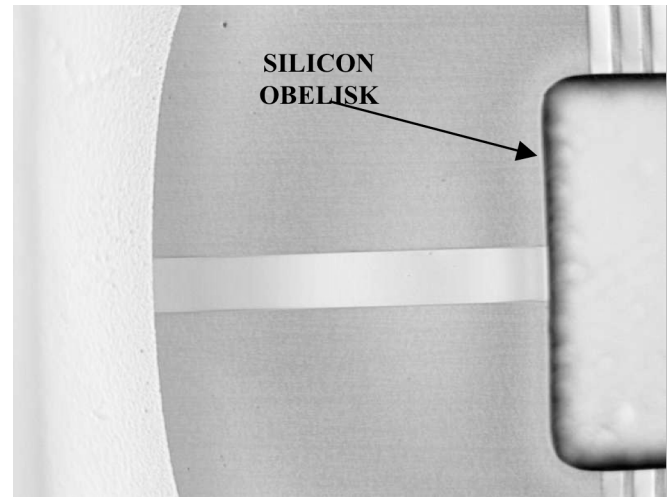
Microfabrication begins with the design of a physical layout on a computer automated design (CAD) tool. The CAD layout may be exported in various standard file formats suitable for the generation of photolithographic masks. The layout data is also valuable for numerical simulation of thermal and electrical properties of the device, and automated means of importing the layout data into 3-dimensional finite-element codes have been developed. The design is replicated such that a 100 mm diameter silicon wafer will accommodate in excess of 300 die in addition to necessary alignment and processing test structures.

The heater resistance and thermal time constant of the device are design parameters that can be varied to provide a design of high sensitivity and good low-frequency performance. The thermal time constant of the device is controlled by the formation of a silicon obelisk directly beneath the heater.

This structure is detailed in Figure 2. A novel deep reactive ion etch process (DRIE) is utilised to produce this feature.



(a) Topside View



(b) Backside View

Figure 2. Microscope image showing the detail of the silicon obelisk feature directly below the thin-film heater. Figure 2 (a) is an image taken from the frontside of the device, Figure 2 (b) is from the backside. The heater and thermocouples on the top side are visible through the transparent thin-film silicon nitride membrane when viewed from the backside.

## IV. VACUUM PACKAGING

Vacuum sealing is being exploited to further increase the sensitivity and thermal time constant of the thin-film MJTC design. This packaging technology is currently under development at Sandia in support of a number of Micro-Electro-Mechanical Systems programs. For the purpose of this work, a 40 pin leadless chip carrier ceramic package has been selected for vacuum assembly. The package has several features that are beneficial, including, the lack of magnetic

material in the I/O pins ceramic construction for hermetic sealing, adequate well size to accommodate the die, and common usage and available tooling (thereby lowering the overall per device cost).

The vacuum sealing process is illustrated in Figure 3. The non-evaporable getter (NEG) material acts as a vacuum pump to relieve outgassing pressure following sealing. The material is soldered to the package lid prior to assembly and requires activation to achieve pumping capability. During getter activation, the package and lid are separated with the lid and getter held at approximately 500 °C. The relative spacing sets the degassing temperature of the package body and die attach epoxy at approximately 240 °C. After getter activation, the lid/getter temperature is decreased to approximately 340 °C, and the package lowered onto the lid to effect a seal.

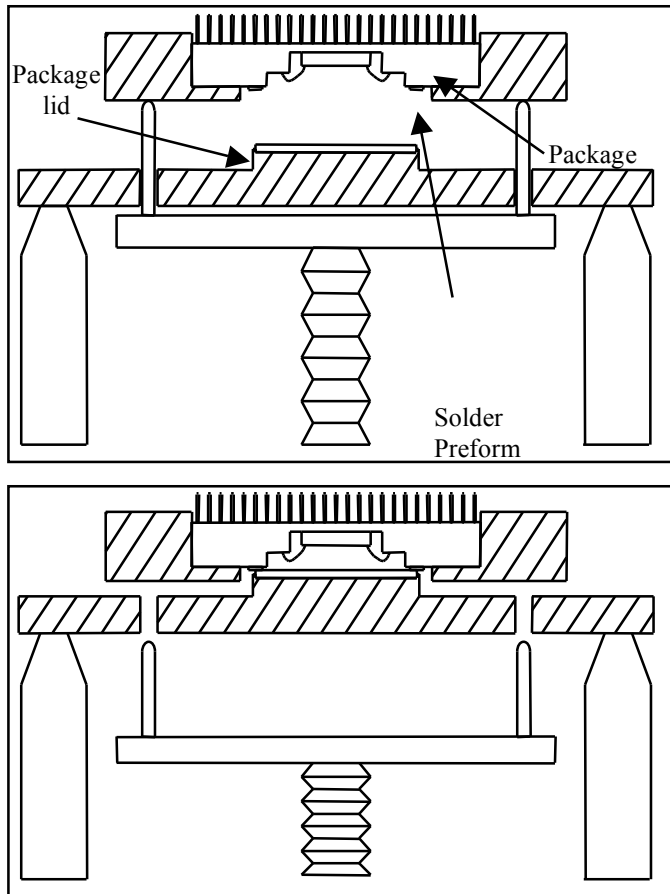


Figure 3. Tooling for the vacuum sealing process. Positioned for getter activation (top) and for package lid sealing (bottom)

## V. MODEL OF THE AC-DC TRANSFER DIFFERENCE AT HIGH-FREQUENCIES

The fabrication of a silicon obelisk, while lowering ac-dc differences at low-frequency by increasing the thermal time constant, has a detrimental effect on ac-dc difference at high frequencies. Klonz, Laiz and Kessler [4] have shown that the capacitance to the substrate and the capacitance from the heater to the thermocouples is insufficient to account for the observed negative ac-dc differences that occur.

A new model incorporating the capacitive coupling to the silicon obelisk has been developed. The model addresses the observed increase in magnitude of the negative ac-dc difference as the heater resistance is increased as well as the negative ac-dc differences at high frequencies.

The physical model attributes the increased heating that occurs on ac excitation to a coupling of the ac signal through the dielectric membrane into the silicon obelisk. The resulting signal that is coupled into the obelisk produces Joule heating within the obelisk that causes an additional temperature rise to occur beyond that which is observed under dc excitation.

In order to accurately compute the magnitude of the observed ac-dc difference, the temperature dependence of the resistivity of the silicon substrate and the voltage dependence of the metal-insulator-silicon capacitor [7] between the heater and the silicon obelisk need to be taken into account.

## VI. TVC ASSEMBLY

The assembled coaxial TVC with the MJTC element and a range resistor or range resistor network is a suitable replacement for single junction TVC assemblies as a high-accuracy, high-sensitivity ac-dc transfer standard. Requirements for a suitable design include proper selection of a low ac-dc difference range resistor, low skin-effect, and control of sensitivity to ambient temperature variation. The assembly is pictured in Figure 4.



Figure 4. Coaxial thermal converter assembly.

## VII. CONCLUSIONS

Replacement of SJTC elements by thin-film MJTC elements requires a device that has low ac-dc differences in the 10 Hz to 1 MHz range. Advances have been made in improving the low-frequency operation of thin film MJTC thermoelements, however, this has resulted in a negative ac-dc difference at high-frequency. While this may be utilized to offset the positive ac-dc difference that occurs due to skin effect, the mechanism for the negative ac-dc difference has not been previously understood. A new model, showing that the capacitive coupling of the input signal into the silicon obelisk is responsible for excess heat generation in the MJTC element provides new insight into controlling the effect by selection of suitable high resistivity substrate material and by tailoring the geometry of the silicon obelisk. Vacuum packaging which also increases the thermal time constant allows a smaller cross section obelisk, increasing the resistance of the obelisk, and thereby reducing the excess Joule heating that occurs.

## ACKNOWLEDGMENT

The authors are grateful for the contributions of Dennis Rieger of Sandia's Compound Semiconductor Research Laboratory in preparing the metal depositions of the thin-film devices and of Jon Custer of Sandia's Advanced Packaging Laboratory for his work in developing the vacuum sealing process.

## REFERENCES

- [1] M. Klonz, T. Weimann, "Accurate thin-film multijunction thermal converter on a silicon chip," IEEE Trans. IM, vol. 38, pp. 335-337, 1989.
- [2] J. R. Kinard, D. X. Huang, and D. B. Novotny, "Hybrid Construction of Multijunction Thermal Converters," 1990 CPEM Digest, pp. 62-63, 1990.
- [3] M. Klonz and T. Weimann, "Increasing the Time-Constant of a Thin Film Multijunction Thermal Converter for Low Frequency Application," IEEE Trans. IM, vol. 40, (1991).
- [4] M. Klonz, H. Laiz, and E. Kessler, "Development of Thin-Film Multijunction Thermal Converters in PTB/IPHT, Proc. Symposium on Microtechnology in Metrology and Metrology in Microsystems, Delft University of Technology, Delft, The Netherlands (Aug. 31 – Sep. 1, 2000).
- [5] T. F. Wunsch, J. R. Kinard, R. P. Manginell, T. E. Lipe, O. P. Solomon, K. C. Jungling, "A New Fabrication Process for Planar Thin-film Multijunction Thermal Converters", 2000 CPEM Conference Digest, Sydney, Australia (2001).
- [6] T. F. Wunsch, J. R. Kinard, R. P. Manginell, T. E. Lipe, O. P. Solomon, K. C. Jungling, "Recent Advances in ac-dc Transfer Measurements Using Thin-film Thermal Converters", Proc. Measurement Science Conference, Anaheim, CA (2001).
- [7] S. M. Sze, Physics of Semiconductor Devices, 2<sup>nd</sup> Ed., John Wiley & Sons, New York, pp. 362-379 (1981).